

## RECENT ADVANCES IN RADAR APPLICATIONS TO AGRICULTURE

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INTRODUCTION

This report summarizes a series of studies now in progress at the remote sensing lab of the University of Kansas, Center for Research. These efforts comprise the geoscience interpretation portion of task 2.5\* of NASA contract NAS 9-10261. Specifically, results and discussion are presented for four studies grouped under the headings: New Approaches and Methodology; Advances in Radar/Agriculture; and Socio-Economic Considerations in Radar/Agriculture. Details of these studies are given in Morain and Coiner (1970), Morain, Holtzman and Henderson (1970), Morain (1970), Coiner and Morain (1970), and Henderson (1971).

RESULTS AND DISCUSSION

The investigations discussed below are diverse in strategy, methodology, and subject matter. They are based almost exclusively on human interpretations as preparation for future automatic data processing. Our guiding philosophy has been that automatic interpretation of such complex phenomena as those manifested in agricultural patterns, is premature until models are devised to direct the construction of algorithms. As Forrester (1970) explains "Computers are often being used for what the computer does poorly and the human mind does well. At the same time the human mind is being used for what the human mind does poorly and the computer does well. Even worse, impossible tasks are attempted while achievable and important goals are ignored (p.2)." We can approach a more realistic and efficient human/computer interface by creating interpretive models of human perception for subsequent, meaningful automation. Some of our more advanced studies, we feel, are nearing that stage.

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\*Task 2.5: Applications and studies of Radar Scatterometers and Radar Imagers to Agriculture and Forestry.

At present all of our agricultural studies center on Garden City, Kansas (NASA Site 76). Two of these investigations are described as advances in approach and methodology while three contribute toward advancing radar/agriculture applications.

## NEW APPROACHES AND METHODOLOGY

Our ultimate goals in agricultural remote sensing in the active microwave are to, first, develop strategies to collect pertinent agricultural statistics exemplified by such measures as acres in production, acres in particular crops, harvested acres, or as input parameters for yield functions; and, second, to make recommendations regarding the parameters of a radar system specifically designed to collect agricultural data usable at several levels in the agricultural hierarchy—local county agents, state agricultural statisticians, and national Agricultural Research Service personnel. To place these goals into perspective we have pursued a new approach and revived a potentially powerful methodology. The first study summarized is an investigation into the information needs of farmers and county agents and an assessment of those needs in terms of radar sensing. The second is an attempt to design and implement radar interpretation keys.

### Basic Remote Sensing Needs in Agriculture

Until recently the information needs of users at primary levels in the agricultural hierarchy (farmers and county agents) have been largely neglected in studies of sensor applications. Yet it is at this level that many of our broadest claims for uses of remote sensor data are made. In July, 1970, data were collected in interviews with farmers and agricultural agents who were directly involved with the farmer. By working at the local level it was possible to determine some of the needs regarding land use and farming practices as perceived by these people. Three counties (Finney, Wichita and Grant) in the high plains of Western Kansas were selected to serve as a study area.

Methodology.—A transect of each county was selected to include a variety of land uses, agricultural practices, and large and small farm operations. One-hundred and twelve farmers located along these transects were interviewed and asked the following questions:

1. Which aspects of your farm and its operation would you like to know better but cannot now determine or predict?
2. What kinds of information might come from remote sensing experiments that would be of use to you?

3. If such information as periodic analyses of predicted crop yields, soil moisture content, or plant vigor were available, how would you use them on the farm?

In addition to individual farm operators, Soil Conservation Service (SCS), Agricultural Stabilization and Conservation Service (ASCS), and Agricultural Extension agents were interviewed and asked: "What information would improve your ability to aid farm operations and farm planning?" Responses to these questions were colored by each individual's perception of his environment and needs, but this is equally true for persons at regional and national levels in the hierarchy and certainly for those designing hardware. These perceptions at all levels, whether right or wrong, must be considered in order to 1) determine where information gaps lie; 2) to assign priorities to information needs; and 3) to develop rational remote sensing programs.

Results. - The list below is a small sample of responses considering the total number of farm types and operations in the United States. Problems paramount in other environments have not been determined but will surely have an impact on the potential usefulness of radar programs. In compiling responses to the questionnaires a decision was made to include only those answers most often given to avoid minor or singular requests. Those designated with an asterisk (\*) indicate possible radar applications. Clearly, many of the problems listed are not amenable to radar analysis or to radar analysis alone. It should be noted also that asterisks do not necessarily indicate the present capability of radar, but potential future ones as well. A complete defense of each present or future application is beyond the scope of this report; consequently a summary statement follows the listing of responses.

Typical responses to the first question were:

1. Proper fertilizer application —optimum time and amount
2. Knowledge of expected market prices early in the planting season
3. Which crops to plant and how many acres per crop
- \*4. More accurate irrigation guidelines - e.g., optimum time and duration
5. How to increase yields
- \*6. Early plant disease detection
7. Insect and disease elimination prior and/or subsequent to field infestation
8. How to cut operation costs

Replies to question two were:

- \*1. Prediction of pests and disease in crops
- \*2. Current field and crop conditions (see Morain and Coiner, 1970 for further details and references)

\*3. When and how much to irrigate

Frequent responses to question three were:

1. To increase profits
- \*2. For more efficient farm management
- \*3. To increase yields
- \*4. To detect and control disease and insects
- \*5. For farm planning
- \*6. To gain knowledge of soil fertility

Five local agricultural officials were asked, "What information would improve your ability to aid farm operations and farm planning?" Their most common replies were:

- \*1. Knowledge relating to the effect of irrigation water on soil, specifically on soil salinity
- \*2. Faster alerts on insect and disease epidemics
- \*3. A better overall picture of a farm than could be obtained by on-the-ground inspection. This included information on:
  - a) drainage and erosion
  - b) optimum land use versus actual use in relation to slope and conservation practices
  - c) better field and building arrangement
- \*4. Pollution control measures
- \*5. Degree of water weed infestation in irrigation ditches and larger water bodies.

These responses indicate that the radar remote sensing community has quite possibly overlooked a basic set of useful applications not specifically requiring crop identification. We have recognized but not yet taken full advantage of radar imagery's synoptic, all weather attributes. For example sequential monitoring by imagers or scatterometers using low incidence angles may prove useful in tracing crop moisture curves and suggesting optimum irrigation dates (responses 1-4; 2-3), harvesting dates, etc. Such applications would require a near continuous monitoring system. The capability for detecting moisture variation has already been shown by MacDonald and Waite (in press). Knowing what crops were in particular fields would not be as important as the  $\sigma^\circ$  vs T (time) for a fixed  $\Theta$ . Radar systems may also have a role in detecting those diseases which very quickly alter crop vigor or which result in defoliation (replies 1-6; 2-2; 3-4). Imagery would be required to monitor the spatial dimensions and directions of movement of these infestations (replies 2-1; 4-2), but scatterometry would be a useful addition for detecting "point" occurrences.

Lastly, a host of less critical needs could be addressed by radar sensors. Water weed infestation (responses 4-4; 4-5) in larger water bodies is certainly within the scope of present capabilities whether

caused by mere availability of water or eutrophication. Since water is a specular reflector with side-looking radars, the protuberance of any vegetational growth would increase  $\sigma^0$ . Such phenomena have already been observed for kelp beds off California and for swamps near Garden City and Horsefly Mountain.

When these kinds of information are combined, a better picture of farm operations on a regional scale may emerge. Regional outlooks on drainage and erosion, field sizes and arrangement, and irrigation dates may all lead to improved farm management schemes. As previously suggested, much of this could be done in the absence of field-by-field crop identifications.

### Design and Implementation of Radar Keys

The dichotomous key concept is not new. Prior to the introduction of numeric clustering methods, this approach was the most common for taxonomic purposes in botany and zoology; and even today it constitutes an important tool in these endeavors (Mayr, 1969, p. 277). In the field of photo interpretation, however, the use of keys is relatively new. They were first devised for use during and after World War II to enhance information extraction from aerial photography. Their widest popularity came during the decade following the Second World War, and several government agencies, including the Forest Service, remain heavily committed to them (Bigelow, 1963). Briefly, the dichotomous key may be defined as, "one in which...description assumes the form of a series of pairs of contrasting characteristics which permit progressive elimination of all but one object or condition of the group under consideration" (U.S. Navy, 1967, p. 57). By use of a binary choice method, it is possible to "key out" certain categories or entities which exist within a heterogeneous group.

Radar Keys in Agriculture. - The most valuable roles for radar sensors in agriculture appear to lie in their ability to 1) obtain synoptic, time-sequential data coverage; 2) perform crop segregation and identification tasks; 3) provide vital agricultural statistics; 4) monitor crop quality or stage of maturity; 5) monitor spatial diffusion of new crop introductions; and 6) provide partial but fundamental input to yield functions.

For agricultural determinations in the active microwave region we believe that interpretation keys will be useful for the following reasons:

1. Since backscattering cross-sections for any given crop type vary continuously as a function of:  $\sigma^0$

- a) system parameters (e.g. frequency, polarization, incidence angle, etc.)
- b) terrain parameters (e.g. moisture contents in plant and soil, soil texture, slope, etc.)
- c) agricultural practices (e.g. row spacing, frequency of irrigation, preference for particular varieties) and
- d) intervening variables such as past weather history, stage of growth and geographic location,

it seems desirable to adopt interpretation methods flexible enough to accommodate a mix of variables at any given time and locality.

2. In any full-fledged sensing program where agricultural statistics are required on a regional scale, it will be imperative that data interpretation take place at a local level, drawing on the knowledge and expertise of county agricultural agents cognizant of present and past conditions in their area. Logically, one of the quickest, most efficient and consistent methods employable for such interpretation would be based on simple dichotomous decisions.

3. The availability of an interpretation key may assist in the integration of information provided by radar into a larger data matrix consisting of aerial photos, ground collected data, and historical records. Conversely, the key may provide a method by which other sensor collected data, ground truth, and historical file data can be used in the interpretation of a radar image. The latter approach has already been applied in an analysis of vegetation at Yellowstone National Park (Hardy and Coiner, 1971).

4. The keys, though based initially on human perception and visual interpretation, can be readily automated into data processing algorithms. Thus, the man-machine interface, which is generally recognized as necessary in remote sensing systems, can be preserved. For reasons stated above, we believe that in the agricultural hierarchy the most effective point for such an interface is at the local (county) level.

Key Construction and Testing. - The format for dichotomous keys can be of two major types: a) a textual, unillustrated form; and b) a textual form supported by visual training aids. The latter is held to be more powerful. A number of preliminary agricultural and natural vegetation keys are being designed and tested. These represent three frequencies (X; Ka; and Ku-bands) for various times in the growing season. All are designed to determine crop types or crop conditions in the commercial grain farming economy of Western Kansas. For areas still in natural vegetation, keys intended to define major plant communities and ecological situations are under study. Our examples so far are drawn from studies at Horsefly Mountain, Oregon and Yellowstone National Park, Wyoming.

Tests of the keys produced to date are encouraging. In addition to providing a coherent and consistent means of interpretation, they seem to reveal a high correspondence between key format and interpreter success. For example, our ability to correctly identify crops using fine resolution X-band imagery was lower than expected, primarily because the design of the key itself was unnecessarily complex. In contrast, on Ku-band imagery having poor visual appearance, interpreters were highly successful, largely because the key was understandable. We have also found that illustrated keys are the most accurate. In some cases, up to 30% more correct identifications were achieved. Additional tests have pointed out that keys offer a range of user alternatives. From any given image, a host of keys can be prepared to yield data for particular interests, thereby allowing interpreters to by-pass unwanted information contained in the image.

In summary, our experience suggests that properly prepared keys increase the validity of interpretations and increase the range of image utility. Dichotomous keys may also solve the need for appropriate agricultural data at all levels in decision making from county through to state and federal agencies. Although the approach is only partially tested at present, interpretation keys seem to provide the best available method for conventional information extraction from SLAR imagery. Our future efforts will be in the areas of format improvement and automation.

## ADVANCES IN RADAR/AGRICULTURE

### Evaluation of Fine Resolution Radar Imagery

In this study, two techniques were used to interpret high resolution imagery\* of the Garden City test site. The first analysis was strictly a visual interpretation of the imagery. Its major objective was to explore possibilities for creating identification keys of crop types and states. Preliminary results have been extremely valuable in: 1) documenting the need for high resolution radar imagery in agriculture; 2) directing the aims of subsequent non-visual studies; 3) highlighting needs for improving terrain data collection; and 4) providing initial experience in the joint use of photographic and radar sensors for identifying crops.

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\* Obtained October 1969 by the University of Michigan X-band system.

The second technique focused on extracting Quantalog spot densities from the X-1 resolution\* and investigating, through a set of categorization strategies, various ways of presenting the data. Film density values for the major land uses at Garden City were displayed in a series of scattergrams representing each of the grouping strategies. The order of presentation of the plots followed a logical sequence in attempting to spotlight the influence of particular terrain and system variables on crop optical densities. In the past (cf. Schwarz and Caspall, 1968; Haralick, et al., 1970), the scattergram method of data portrayal has often been used but never thoroughly evaluated for its worth in isolating the influence of particular variables. For a more complete discussion of the scattergrams see Morain and Coiner (1970).

Results indicate that the unconstrained plotting of all densities, irrespective of crop purity, incidence angle, etc. can distort the data and complicate its interpretation. Better segregation of crops in measurement space (HH vs. HV density) can be achieved if differences such as incidence angle, crop purity, row direction, stage of growth, and combinations of these, are taken into account. Nevertheless, spot densitometry derived from 2-polarization, single pass imagery will, by itself, rarely give unambiguous crop discrimination. Multiple "looks" throughout the growing season will be required if image tone is to be the only discriminant. Distinctions impossible to make in October may be quite possible earlier in the growing season or with a different frequency, polarization, incidence angle, or look direction. Both look direction and incidence angle are shown in this report to have significant effects on the return signal for particular crops.

Visual Interpretation. - The following paragraphs outline image appearances on a crop by crop basis. It is from such observations that visual interpretation keys are constructed. Only the more economically important crops are discussed.

**Sugar Beets:** By October, the sugar beet crop at Garden City is fully matured and ready for harvest. In healthy fields at this late date in the season, canopy shape and moisture content are probably the most important factors affecting radar backscatter. The most characteristic features of beet fields are their consistently high return and their tendency to strongly depolarize radar signals. They appear on both the HH and HV images in very light to light grey uniform tones. Only one field out of those compared had a conspicuously darker tone than the others. Whether this arose from image darkening by antenna pattern or an unhealthy (perhaps moisture stressed) field is uncertain. Degree of depolarization, as a discriminant, is at present only useful on individual passes of the aircraft where gain settings on the HV term can be assumed to be reasonably constant. Discrimination of sugar beets from

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\*X-1 resolution refers to the best resolution presently obtainable.



its nearest appearing ally, maturing alfalfa, can often be accomplished using degrees of tone difference between polarizations. This appears to be possible, however, only up to a point in the alfalfa cycle; beyond that there is little difference between the HH-HV tones of these crops.

By using both the HH and HV polarizations and noting in particular the degree of tone shift and absence of within-field patterns, confusion with other crops can be largely overcome. In short, as was observed by Simonett, et al. (1967), sugar beets can be easily discriminated at this time of year on X-band imagery.

Sorghums: In 1969 sorghum as a category covered more acreage than any other crop present in the test site. It is not an especially well defined crop, however, since it includes forage sorghums exceeding six feet in height at one extreme and grain sorghums three to four feet high at the other. In addition, there are extreme differences in crop canopy and geometry between these sub-categories. In order to reduce this complexity, forage sorghum (mainly sudan) was separated from the grain subtype. Fields of grain sorghum were again subdivided depending upon whether the planting direction was orthogonal or parallel to the look direction. In the following discussion only grain sorghum is considered.

By early October grain sorghum is ready for harvest. The gross canopy geometry consists of two entities: a lower leaf stratum which is nearly continuous from any viewing angle; and an upper, more vertically oriented layer of emergent stalks and grain heads. Differences in tone from field to field are significant and from all evidence arise from differences in row direction. Specifically, we believe that differences in radar return this late in the growing season are associated mainly with the height of the head and the progress of ripening.\* When the signal is scattered from rows oriented perpendicular to the look direction, the major part of the return (at the higher incidence angles)\*\* may be coming directly from ripe grain heads. If the rows are oriented parallel to the look direction however, backscatter is more likely described as a complex interaction involving leaf, stalk, and head. Additional very detailed research on particular fields will have to be undertaken to firmly establish this relationship.

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\*We have seen numerous fields on the Michigan imagery which appear to show differences in crop condition. Some of these differences are known to coincide with uneven ripening within fields which may in turn be a function involving plant and soil moisture as well as soil type.

\*\*In the Michigan system all incidence angles are  $\geq 69^\circ$ .

In general, sorghum fields ranged in tone from dark to light grey. Those with row directions orthogonal to the look direction were consistently darker in both polarizations than those planted with rows parallel to that direction. Grey scale variation from HH to HV showed little or no consistency regardless of row orientation. However, the HH to HV variation was somewhat less pronounced in those fields with rows perpendicular to the look direction. Tonal variations in fields of the same row direction and ripeness were also noted. Though we have no firm explanation for this phenomenon at present, we can be fairly confident that terrain parameters are a fundamental influence.

The difference in return related to row direction is more complicated than increase or decrease in return would suggest. In those fields with rows perpendicular to the incident signal, slight mottling in the illumination may arise. We believe these effects are related to local differences in crop height, moisture content, or degree of ripening (see also the discussion of K-band imagery by Simonett, et al., 1967).

Due to the broadness of the sorghum category and the range of reflectivities inherent in such a grouping, discovery of a completely unambiguous interpretation aid based on a single mission is not possible. Nonetheless, when one narrows the category to include only fields of grain sorghum with rows perpendicular to the line of flight (i.e., parallel to the incident signal), there is sufficient consistency of image tone and "texture" to suggest that interpretations using dichotomous keys should be fairly reliable. Sorghum fields, particularly on the HV, display a medium coarseness of texture which seems independent of the field's grey level. This texture and the within-field tone homogeneity are the best indicators for grain sorghum presently derivable from the Michigan imagery.

Wheat: By Fall, three broad types of winter wheat are recognizable in Western Kansas: 1) fields of recently planted and just emerging wheat—approximately 3" in height and covering a small percent of the ground; 2) developing wheat, planted in late August or early September, which by October is 6 to 8" in height and covers most of the ground; and 3) almost continuous volunteer regrowth from the preceding June harvest. The geometric similarity between fields of volunteer wheat and those with developing wheat higher than 3" dictates that these two types be considered as a single category.

Those fields which contained emergent wheat display mottled patterns within fields similar to those observed in sorghum. This spotty pattern varies from light grey to black and is characterized by a very fine "texture" in the light grey portions. These two attributes are most useful in discriminating emergent wheat. In contrast, those

fields with a more continuous cover and greater height, normally image in lighter tones. Equally important as discriminants, developing and volunteer wheat fields usually do not display evidence of cultivation patterns. In general, they have more uniform illumination and can occasionally be confused with sugar beets.

Neither of the wheat sub-categories varies substantially in tone from HH to HV except for the quadrants in emergent wheat in which the cultivation direction is orthogonal to the look direction. Both are subject to confusion with some types of fallow. However, discrimination can frequently be achieved between wheat and fallow on the basis of HH to HV variation. Fallow fields often appear mottled in the HV, while wheat normally does not.

Corn: This late in the growing season, corn is fully mature and is undergoing harvest. However, as is equally true of grain sorghum, delays in planting, timing of the final irrigation, and variations in ripening and drying rates all insure that minor differences (mainly in moisture status) exist between fields. By experience, farmers have learned to recognize when their field is uniformly dry enough to harvest and until that time arrives, the crop is left standing. Late in the season, then, one of the inherent characteristics of standing corn is non-uniformity within fields. A second defining attribute is height. Corn is normally the tallest crop encountered in Western Kansas, often reaching 8-10 feet. Its nearest rival is sudan grass—a type of forage sorghum occurring very infrequently.

Uniform, mature fields usually appear in medium grey tones, and much of the grey range arises from inhomogeneities (mottling) in both the HH and HV terms. Causes for these differences, appear to vary between polarizations. A comparison of the SLAR return with both Ektachrome and CIR failed to suggest a single source for the in-field variation, although in some cases the mottled tones could be related to suspected differences in the rate of crop maturation. Unlike sorghum, no overall trend in HH to HV shift could be derived.

Alfalfa: The crop cycle of alfalfa makes it a difficult crop to interpret. By October, fields may range in height from 6" to 24" and may be in any of several irrigation states. However, by splitting alfalfa into two sub-categories (under 12" and higher than 12"), it is possible to make fairly reliable distinctions.

Alfalfa less than 12" high (i.e., recently cut) images in dark grey to medium grey tones on the HH polarization. One of its most reliable features is the series of lineations which is always parallel to the longitudinal axis of the field. The cause of these is almost certainly associated with diking for flood irrigation. Another important

discriminant for this category is the tone shift from HH (dark) to HV (light), the trend being just opposite from that observed for other crop types. The increase in return on HV imagery might arise from the short, vertically oriented "stubble". To vertically polarized radar signals the field would appear, in analogous terms, as a short bristled brush, with a fairly high moisture content. Theroretically this phenomenon would be truer at high incidence angles than at low, and at the extreme (90° depression  $\lambda$ ), there should be no influence at all. Moisture must be an important factor because wheat stubble with the same basic geometry but lower moisture content gives lower returns than alfalfa. The moisture content of cut alfalfa averages 70-80 per cent, while wheat stubble is generally less than 10 per cent.

After alfalfa has grown to about 12" its appearance on HH imagery begins to be more uniform; that is, lineations begin to disappear.\* By the time the crop reaches full maturity (24"), complete homogeneity has been attained. Moreover, mature crops display little or no tone shift from HH to HV. We suspect the cause for these attributes lies in the density and uniformity of the alfalfa canopy as well as with the size and orientation of leaves.

Recently Tilled Fields: Recently tilled fields represent an easily distinguishable category. They nearly always appear as a uniform dark grey or black tone. This category includes those fields cultivated one to two weeks before the mission and observed at the time of field inspection as clean, vegetation free surfaces. Unfortunately, detailed data are lacking on the types of tillage operations performed or their effect on radar returns. Our reasoning at present is that operations like row harrowing, which completely turn the soil, tend to decrease backscatter more than disking. Recently tilled fields can be discriminated on the basis of their dark tone and similar appearance on both polarizations.

Crop Discrimination by Spot Densitometry. - Crop discrimination was attempted with the Garden City imagery using a Macbeth Quantalog spot densitometer. Spot densities were recorded on the HH and HV negatives of the X-1 resolution using a 1 mm aperture. Four strategies were then employed to see if the data spaces of particular crop categories could be separated from each other on the basis of their HH and HV film densities. These were as follows: 1) to plot the entire data set irrespective of field quality or viewing angle; 2) to plot the entire data set partitioned according to location (incidence  $\lambda$ ) on the imagery; 3) to plot selected, high quality fields irrespective of viewing angle; and 4) to plot selected fields partitioned according to location across the image.

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\*This fact indicates that canopy penetration at X-band is almost non-existent. Once the crop is high enough to mask the diking, the lineations disappear.

Bearing in mind that the Michigan radar system utilizes a very narrow range of incidence angles (ca 16°) tables I-A and I-B list the kinds of crop separations achievable using strategies 2 and 4 above. When the HH-HV densities of all fields are arranged into incidence angle classes (table I-A) confusion arises in distinguishing many of the crops, particularly grain sorghum, wheat and alfalfa. By making an initial selection of high quality fields (table I-B) many of these ambiguities can be minimized. Moreover, there are sound theoretical and practical reasons for making such a selection. First it is axiomatic, though not 100 per cent true, that high quality, clean fields account for most of the yield for a particular crop; and second, in these early stages of model building, simplification of the problem is essential.

#### Agricultural Determinations from Fine Resolution Imagery

It should be noted that the Michigan imagery was obtained in early October, a suboptimum time in terms of crop calendars. Few crops are present this late in the season and those remaining are all on the down-slope side of their annual moisture curves. This results in reduced variance in terrain backscatter and greater difficulty in making determinations. While some determinations are possible using scattergram methods, the inability of the Michigan system to yield better results than the Westinghouse system (flown in September 1965) must be viewed in context of the cropping calendar.

The use of fine resolution imagery promises great improvement in our ability to accurately assess within-field variations. Aside from making interpretation keys, patterns resulting from differences in crop backscatter have given our first encouraging evidence that ripeness (or crop state) could be monitored through a function of crop moisture. From theoretical considerations we suspected this capability but, until the availability of fine resolution data, we had not actually observed the phenomenon.

The availability of fine resolution imagery has dramatically focused attention on the need for refining the collection of field data. We are now sure that factors such as crop purity, tillage patterns, soil type, crop moisture and a host of other variables must be studied in greater detail than heretofore necessary with coarser resolution systems. Some parameters must be better known in order to advance directly the preparation of interpretation keys; others because their influences are ultimately manifested in crop attributes used in the keys.

#### Comparison of Radar Systems for Agricultural Determinations

With this report we have to date prepared scattergrams from the imagery of three radar systems. Westinghouse AN/APQ-97 and NASA

DPD-2 imagery represent two separate frequencies in K-band; while the Michigan imagery is X-band. Since the data for all three were obtained over a one month period from September 4 to October 4,\* a brief comparison of their utility in distinguishing land use categories is in order. Data are also included from a fourth scattergram constructed from AN/APQ-97 imagery from July 1966 (Table II).

In making comparisons one must remember that different viewing angles and look directions are represented in each of the images and that the procedure for producing the plots was not standardized. For example, second generation negative transparencies were used for the Westinghouse analyses, but a positive transparency was used with the NASA data. Spot densitometry was used on the Michigan and NASA data, but line trace densities were taken from the Westinghouse imagery. We have no information on the relative merits of these various techniques.

More important differences occur in the plotting strategies. The Westinghouse data were plotted irrespective of viewing angle or field quality. NASA data from the DPD-2 attempted in a qualitative way to take viewing angle into account; and with the Michigan system both viewing angle and field quality were accounted for. General indications from Table II are listed below.

1. Fine resolution imagery exemplified by the Michigan system is not necessary or even particularly valuable in the late growing season solely as an aid to crop segregation by densitometry. Partly this may be due to uniformly low moisture status for all crops and of uncropped land at this time of year (see Schwarz and Caspall, 1968, p. 241).
2. At the opposite extreme (that is, uniformly high moisture status during the height of the growing season), fine resolution imagery would probably not be of great benefit over that from systems of coarser resolution in gaining optical density information. This is indicated by the fact that: a) both the July and October data compare favorably in relative information content; and b) the July and September 15 data from the same system differ markedly in their information. During the height of the growing season all crops have a high moisture status, consequently (in terms of crop dielectric properties) the influence of moisture on backscatter cannot be widely used as a discriminant.

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\* Westinghouse AN/APQ-97 September 15, 1965; NASA DPD-2 September 4, 1969; and Michigan System October 4, 1969.

3. The data suggest that if only film density is used as a discriminant, optimum periods for crop segregation might occur in a narrow time interval around the middle of September when maximum differences exist in both moisture status and crop geometry; or in early May before the full complement of crop types enters the land use picture.
4. There might be sufficient frequency dependence between crops that a dual-polarized polypanchromatic radar flown in mid September could perform the task of crop discrimination. Alfalfa, which could not be isolated in two-space by Ka-band on September 15, was at least partially discriminable by Ku-band somewhat earlier in the season. If such contrasts were optimized, various training and prediction processes for automatically identifying crops might prove more successful. Unfortunately, it could be argued that mid-September is too late in the growing season to make very many useful economic predictions.

#### Radar Soil Mapping

Several investigators have reported on the scope for soil studies using radar imagery as a base. Simonett, for example, (1968) was able to distinguish four soil associations in Woods County, Oklahoma near the dry/subhumid boundary. These were largely restricted to uncultivated areas such as badlands, salt plains, floodplains and terraces. On adjacent cultivated land, soil texture patterns were masked by complex crop geometries and variable moisture patterns. Barr (1969) found that regional engineering soil types could be identified by inference combined with recognition of repetitive patterns. In his study it appeared that brute force systems yielded higher quality data than synthetic aperture radar, but given the present state-of-the-art in these type systems, this is not surprising. Since there was little penetration at the wavelengths used by Barr, the reflecting surface was found invariably to be the first surface intercepted by the signals. In desert regions in particular (an environment under investigation at Kansas) that surface is usually a combination of rock or bare soil and desert shrub. The low density of plants per unit area, together with a wide range of soil textures over short distances, leads one to suspect that significant soil information might be derived from the radar frequencies.

Figure 1 is a reproduction at original scale of Ka-band imagery  $\lambda = .8-.9$  cm obtained over Tucson in November, 1965. The valley region is devoted largely to irrigated agriculture and, as Simonett found in his studies in Oklahoma, the soil pattern is mostly obscured. Large areas on the alluvial fans and smaller areas along the valley

(particularly adjacent to the Santa Cruz River) reveal a pattern closely resembling that mapped by the USDA Soil Survey (Young, et al., 1931). Vegetation throughout the uncultivated area consists of Creosote bush (Larrea divaricata), scattered Mesquite (Prosopis juliflora) and Burroweed (Haplopappus tenuisectus). It is improbable, therefore, that the patterns on the imagery are due to defineable plant communities. In Figure 2 boundaries have been delineated from the radar by combining information from the like (HH) and cross (HV) terms. Once delineated, the areas were categorized through reference to the pre-existing soil survey map compiled in 1931. A complete set of texture types including broken and stony land, coarse textured pebbly and sandy soils, silt loams, loams and clay loams resulted from this categorization. Highest returns on the imagery are observed for the stony and pebbly soils. These surfaces are apparently behaving as isotropic scatterers, perhaps because of the angularity of the sand grains comprising the surface and the comparability of their size to that of the transmitted wavelength. Generally, as texture becomes finer, radar return diminishes: loams, clays, and clay loams image as medium to dark grey tones, while silt loams image almost black. The apparent anomaly of silt loams imaging darker than clay loams in what is otherwise a consistent trend may be explained by the fact that, in this area, the Gila silt loam characteristically melts together to form a smooth surface reflecting the bulk of radar signals away from the receiver.

The patterns on Figure 2 can be compared with a simplified version of the USDA soil map illustrated in Figure 3. The major difference between them is that the cultivated area has expanded since 1931. Most of that expansion has involved soils of the Gila series. The overall correspondence in pattern is striking and suggests that interpreters knowledgeable about local soil-vegetation-topography relationships could produce reconnaissance or semi - detailed soil maps from radar. Much research still needs to be done, however, to define  $\sigma^0$  for various soil textures and conditions, as well as moisture contents, at specified frequencies and viewing angles.

Consistency of radar backscatter is, of course, an important issue in mapping any terrain phenomena. It is encouraging, therefore, that exactly the same texture/backscatter trend has been observed and mapped near Tule Mountain in the Trans-Pecos of southwest Texas. In this locality broken and stony land was separable on the basis of terrain texture and drainage patterns. Very gravelly loam, representing the Reeves series, imaged in medium gray tones, and, as texture became finer in the Ector and Rio Grande series, backscatter intensity diminished.



## Socio-Economic Considerations in Radar/Agriculture

For any sensor system time is a key discriminant. Research on the spectral reflectivities of plants has shown that instantaneous unique signatures are unlikely to exist and that time-sequential imaging may be required to identify crops (Haralick, et al., 1970; Park, 1969; Wiegand, et al., 1970). Basically there are two temporal frameworks in which to work: seasonal and year-to-year. Under both rubrics there exist within- and between-crop radar variations, but the economic and social implications attendant upon each are vastly different.

Between-Crop Seasonal Variations. - It is not, in fact, the ability of radar to collect useful information that stymies its wider application, but our ability to interpret the data. As Haralick, et al., (1970) point out, it will take a Herculean effort to create automatic data processing routines for crops whose spectral properties vary continuously in time and space. Wheat, the world's most important crop, is produced in scores of varieties under as many cultivation practices. Clearly, it is unrealistic to expect radar or any other sensor to provide interpretable agricultural data without knowing the nature or magnitude of within-crop geographic and phenologic variations. Basically, the problem reduces to knowing which radar and terrain parameters are critical in making accurate land use identifications. In searching for these we have overlooked one of the simplest, most useful aids to identification yet devised — the dichotomous key.

Provided imagery can be disseminated quickly enough for primary agencies to interpret the data in at least a sampling framework, improvement in statistics from crop reporting services could be realized. Bernstein and Cetron (1969) have indicated that techniques should be available for disseminating inventory information from large data banks by 1975. At present, data are gathered by an army of volunteer observers in coordination with regularly mailed questionnaires. By the end of the year, it is often true that acreages and yield predictions for wheat in the Great Plains are accurate to within 3 per cent. However, predictions prior to harvest are often gross estimations. It is not in improving accuracy for which radar holds great promise but in providing early estimates and in decreasing uncertainties inherent in the predictions.

Prompt and efficient interpretation of radar imagery generated at regular intervals throughout the growing season could dramatically improve such statistics as number of acres in particular crops, progress of harvest, number of acres harvested and others. All of these would result in better planning at the county and state level, even if the margin of improvement in accuracy were small.

Within-Crop Seasonal Changes. - The most important aspects of within-crop seasonal change are those subtle differences associated with crop quality or variety. Both are part of a complex yield function, the discerning of which lies at the foundation of agricultural reconnaissance. With the "Green Revolution" in progress in Asia (Wharton, 1969), it is imperative that both acreage and variety be considered in production estimates.

At present there is no evidence that radar, or any other sensor, can detect (at acceptable levels of confidence) differences between varieties, let alone identify them. There may be hope for some estimates, however, by using surrogates related to time (if some varieties ripen earlier or permit double or triple cropping) or space (if they occur in restricted localities) (Brown, 1968). Unlikely to be detected are small differences in  $\sigma^2$  arising from increased head size, longer stalks, or other geometric parameters. For the foreseeable future, it seems that radar's most valuable contribution to yield prediction rests largely with acreage calculations inserted into a more comprehensive yield function.

Crop quality information derivable by monitoring might be useful. As a parameter of the yield function, cause of poor quality is not important. It is sufficient to know simply that low quality fields are typically low yielders and should be weighted accordingly in making production predictions. However, if causes and effects can be related by using radar, tremendous economic benefits accrue. By following the rapid expansion of diseased areas or by tracing damage along storm tracks (both of which demand near all-weather capability), assessment of economic loss or preventive measures could be quickly made. The cost of monitoring would be small compared to the savings. In Kansas alone, loss of sorghum from aphid infestations, which spread across the state in two weeks, amounted to \$14,733,000 in 1968-69 (Kansas Board of Agriculture, 1970).

Year to Year Changes Between Crops. - The benefits of long term agricultural sensing have not been seriously considered. Land use histories compiled from data collected over the years and stored for rapid retrieval could be useful in developing production control measures. In higher echelons there is a tradition of juggling the amount of land planted to control surplus and deficit (Doll, et al., 1968). However, problems of cross compliance and input substitution have hindered any startling successes. By using automatic data processing, accurate regional histories and local land use trends could be mapped. Such projects are not possible today because historical records of field size, crop type, or production are not available. It would be highly desirable to trace diffusion rates and directions of new crops (varieties?) or

the development of farm-to-market road nets (Brown, 1968) and to follow the geographic spread of innovation such as the use of polyethylene protectors on sugar beet seedlings or the progress of land reform policies. Efficiency of production has been the keynote of 20th Century agriculture; yet, the policies instituted to achieve that efficiency are mostly based on aggregate\* statistics rather than detailed local data. Disaggregation may hold promise for substantially improving agricultural economic theory, and for this reason alone radars may prove their value by supplying synoptic coverage of any desired region.

Year to Year Change Within Crops. - The least studied aspect of agricultural surveillance, the gradual changes in crop reflectivities over the years, may ultimately be the most important in aiding plans for world food supplies and production, since these indicate the spread of the "Green Revolution" or improvements in crop vigor. Most of the increase relates to gradually improving yields, which leads us to agree with Pendleton (1970) that the concept of a "yield plateau" is a myth. Increasingly, man must rely on greater production from each acre to feed expanding populations. The best mechanism for doing this is by creating better varieties and engaging in other forms of input substitution; namely, fertilizer application, irrigation, etc. We are quite uncertain how radar will prove economically beneficial, but certainly a most worthy pursuit would be to explore the numerous possibilities.

#### In Future

We have attempted in this brief summary to place into socio-economic perspective a number of possible applications and benefits of radar sensing in agriculture. Some of these applications (e.g., cultivated land inventories and selected crop acreages) should be realizable within a few years with continued research and technological advances. Others are further down the research road and others, yet, may never be achievable. Even though firm cost/benefit ratios are not yet calculable, we are convinced of the economic desirability of using radar to obtain basic agricultural statistics. At this point, however, society demands that we address even more pervasive social and political questions. We are already near enough to attempting some of the stated capabilities (perhaps five years) that fears are surfacing regarding attitudes among the farming community and among foreign peoples and governments toward the unseen and all-seeing sensor. Exceedingly complex legal and social problems will attend agricultural monitoring programs, and it is time we anticipate these issues.

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\*Aggregate statistics refer to averages rather than individual values. See for example, Grunfeld and Griliches, 1960.

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TABLE I-A SEGREGATION OF CROP GROUPS ON THE  
BASIS OF RADAR RETURN AND VIEWING ANGLE  
(All Fields)

	Low Radar Return	Medium Radar Return	High Radar Return
Low Incidence	Bare	Grain Sorghum, Corn, Wheat	Sugar Beets , Alfalfa
Medium Incidence	Bare	Grain Sorghum, Weeds	Wheat , Alfalfa , Sugar Beets
High Incidence	Bare , Wheat	Wheat , Alfalfa	Grain Sorghum, Sugar Beets , Corn

TABLE I-B SEGREGATION OF CROP GROUPS ON THE  
BASIS OF RADAR RETURN AND VIEWING ANGLE  
(Selected Fields)

	Low Radar Return	Medium Radar Return	High Radar Return
Low Incidence	Bare	Grain Sorghum , Corn	Sugar Beets , Alfalfa
Medium Incidence	Bare	Grain Sorghum	Sugar Beets , Alfalfa
High Incidence	Bare	Grain Sorghum , Wheat , Corn	Alfalfa

TABLE II. PERCENT CROP SEGREGATION\*ON SCATTERGRAMS AS A  
FUNCTION OF RADAR FREQUENCY AND DATE IN THE GROWING SEASON

Date and Radar System	7/66	9/4/69	9/15/65	10/69
	Westinghouse AN/APQ-97 Ka-Band	NASA DPD-2 Ku-Band	Westinghouse AN/APQ-97 Ka-Band	Michigan X-Band
Wheat	Not present	- - -	- - -	77
Grain Sorghum	82 (cropped)	- - -	69	
Corn		28	92	
Alfalfa		50	- - -	64
Sugar Beets	92	- - -	97	
Bare Ground	91**	90	83	91

\* Calculated as a percent of all fields comprising the fractional codes, NOT as a fraction of all fields of a given crop type. For example, grain sorghum on Westinghouse imagery for September 1965 comprised 69 per cent of all crops contained in the data space bounded by an upper and lower hyperplane, but almost 95 per cent of all grain sorghum fields plotted on the scattergram occurred within that data space. In other words, while most of the sorghum fields occur within a fairly well defined data space, they cannot be unambiguously discriminated from a host of other crops.

\*\* Including wheat stubble.



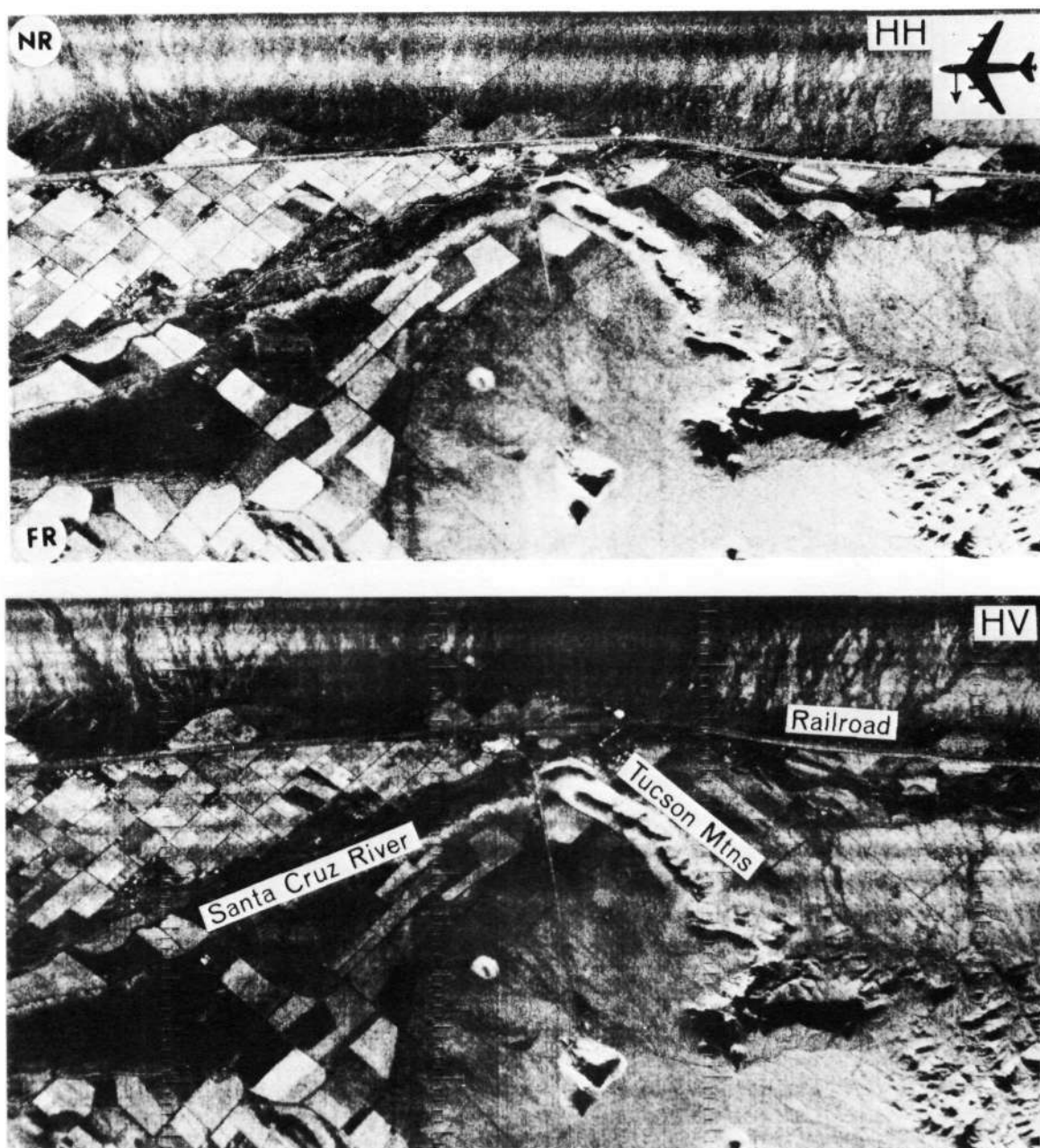


Figure 1. K-band radar imagery near Tucson, Arizona. Note soil patterns revealed on alluvial fans surrounding Tucson Mtns. and on slopes north of railroad line. Pattern in valley is partly obscured by agriculture.

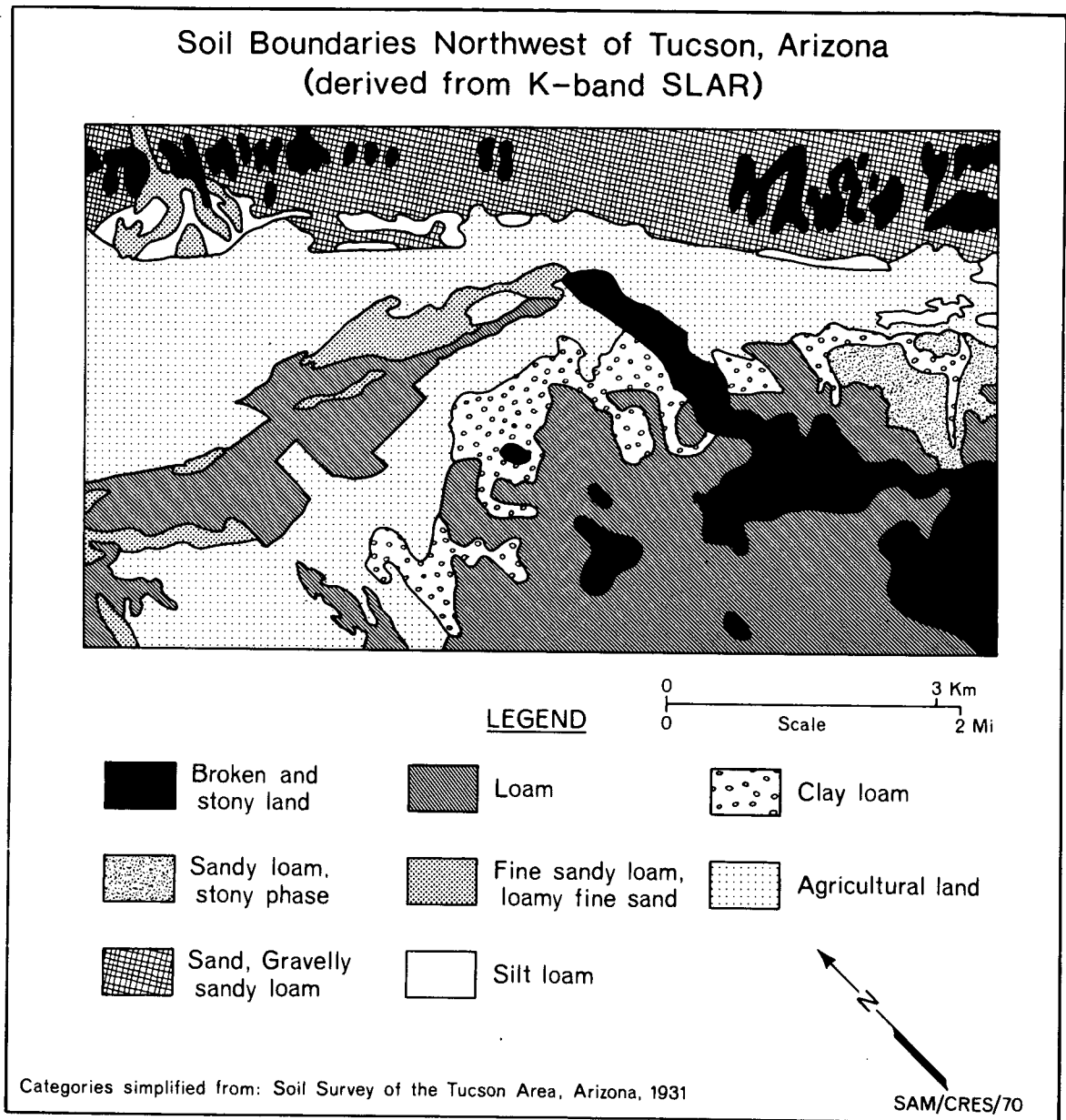


Figure 2.

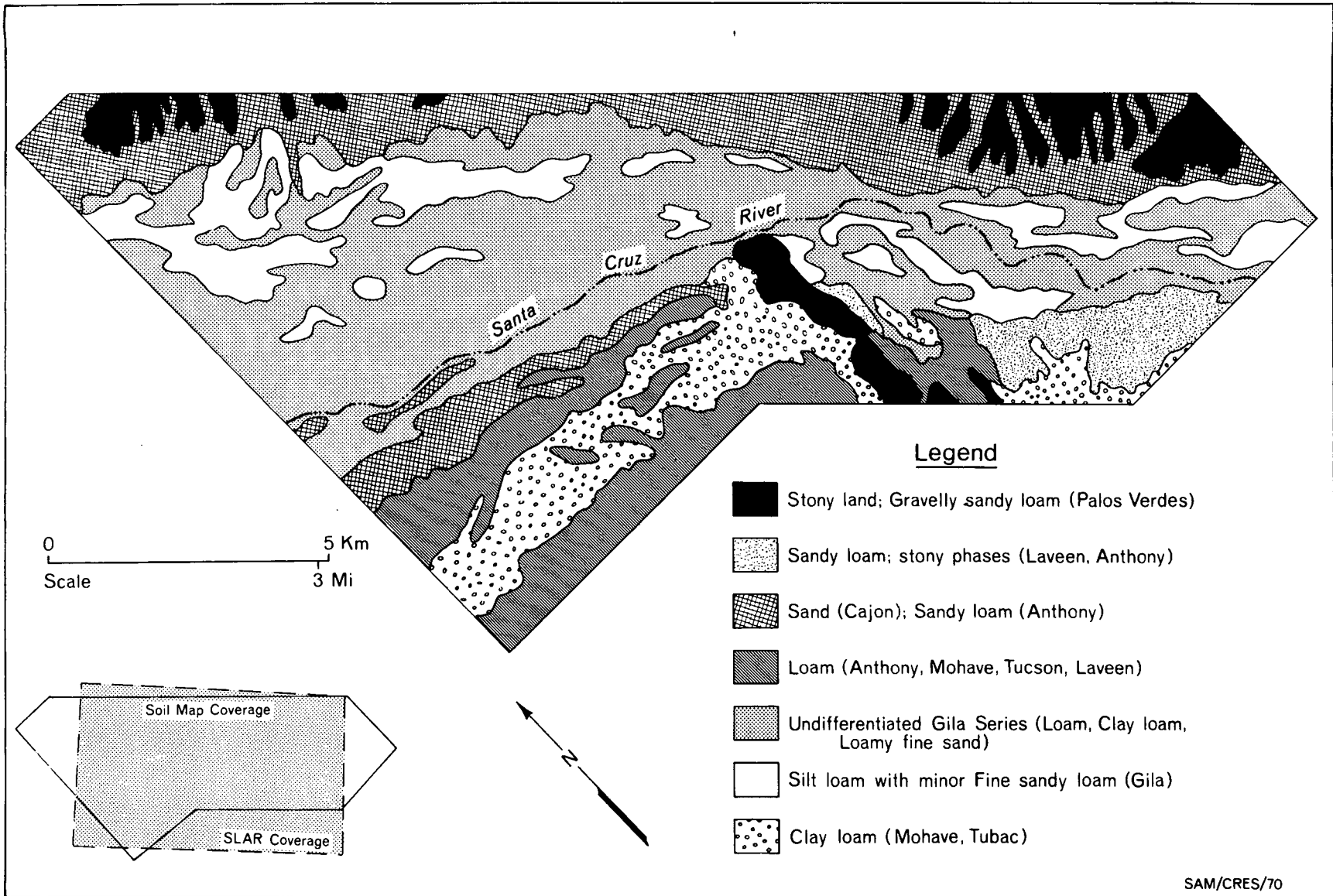


Figure 3. Soil types of the Tucson region simplified from USDA Soil Survey Map of 1931.